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SPACE REACTOR FUEL PERFORMANCE AND DEVELOPMENT ISSUES

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ABSTRACT

Three compact reactor concepts are now under consideration by the U.S. Space Nuclear Power Program (the SP-100 Program) as candidates for the first 100-kWe-class space reactor. Each of these reactor designs puts unique constraints and requirements on the fuels system, and raises issues of fuel systems feasibility and performance. This paper presents a brief overview of the fuel requirements for the proposed space reactor designs, a delineation of the technical feasibility issues that each raises, and a description of the fuel systems development and testing program that has been established to address key technical issues.

MISSION POWER REQUIREMENTS

A set of preliminary design goals for the SP-100 system have been defined (1). The most notable of these are that the power system must produce at least 100 kWe of power, that it have a mass of less than 3000 kg, and that it must fit into one-third of the space shuttle bay. The specification of a 100-kWe power output to the payload is based on the requirements of a number of potential civilian and military missions. Among these are communications and surveillance satellites, space-based radar systems, space station support, and manufacturing in space. The weight and volume constraints arise because, as indicated, the space shuttle will be used to carry the SP-100 system into low earth orbit from which it will be boosted into space with an auxiliary rocket system. To accomplish this, the SP-100 system must fit, along with its associated hardware and rocket boost system, into the cargo bay of the space shuttle, and be of such weight that it can be accommodated by the shuttle propulsion system. An additional requirement, although not formally specified, is the desire to launch a flyable reactor system in the early 1990s. This, of course, imposes a definite limitation on the time available for assessment and development of candidate reactor and power conversion technologies.

CANDIDATE REACTOR SYSTEMS

During 1983, the SP-100 project management, with the assistance of technical experts from industry and government laboratories, considered a wide range of potential reactor concepts to meet the SP-100 system requirements (2). In all, several dozen combinations of reactors, heat transport technologies, and conversion systems were considered. From among these, the field has now been narrowed to three that appear to be best suited to meet the SP-100 operating requirements.

1. A low temperature reactor utilizing a modest extension of liquid-metal fast breeder technology coupled to an advanced free-piston Stirling conversion system. This reactor, which would operate in the 900-1100 K range, features UO_2 or UN fuel clad in stainless steel or Nb-1Zr. The primary heat transport system would use pumped liquid Na or Li as a coolant.

2. A pumped liquid-Li-cooled, pin type reactor designed to operate at about 1500 K coupled to an advanced thermoelectric converter. This system would incorporate UO_2 or UN fuel clad in Nb-1Zr-0.1C, Mo-13Re, or W-25 Re. A Ta-based alloy (ASTAR 811C) is also under consideration as a cladding material in this system.

3. A high temperature (~1700 K), UO_2-fueled reactor featuring an in-core thermionic conversion system with a pumped NaK primary coolant loop. At present, the thermionic conversion system utilizes a W emitter and a Nb collector.

These three candidate reactor systems will command the focus of the remainder of the technology assessment and advancement phase of the SP-100 Program with the intent to narrow this group to the most feasible single concept for further development in the subsequent ground engineering systems test activities scheduled to begin in mid 1985.

FUELS SYSTEMS PERFORMANCE REQUIREMENTS

As detailed above, three candidate reactor systems have been defined to meet the functional requirements of the SP-100 Program. These requirements can be best met by a compact, high-temperature fast reactor system coupled to an advanced static or dynamic electrical conversion system. From this definition, a series of generic fuels systems performance requirements have been identified, and a technology assessment and advancement effort has been initiated to supplement existing knowledge regarding the likelihood that the proposed fuels systems can meet such requirements. For the three reactors under consideration, two major technical feasibility issues have been identified (1). These are: fuel swelling and fission product behavior during irradiation and fuel-cladding-coolant compatibility at operating temperatures. These issues, by definition, are considered to be potential "show stoppers" crucial to the basic functioning of the reactor core.

Fuel Swelling and Fission Product Behavior

During the burnup of the fuel in reactor operation, the fuel stoichiometry is continuously changing and fission products are being formed. Depending on the fuel fission rate, and fuel temperature and thermal gradient, insoluble fission products can migrate from the points of formation in the fuel atomic lattice to voids and grain boundaries where they accumulate and form gas bubbles. This nucleation and coalescence of fission products in the interstices of the fuel, results in volumetric swelling, and, ultimately, cracking of the fuel can occur releasing fission products to the external surfaces of the fuel. Fuel swelling and fission gas pressure, exerting unacceptable stresses on the cladding material, represents one of the major life-limiting factors in f t reactor systems.

At the lower temperature range of interest to the SP-100 Program (<1500 K), some data on UO_2 and UN swelling and fission product behavior exists (3). However, all of these data are from relatively low burnup (<3%) irradiations conducted in a thermal reactor. The lack of both data and a mechanistic understanding of UO_2 and UN reactor-fuels behavior, under the specific operating conditions envisioned for the mid- and high-temperature SP-100 reactors (long lifetimes, high burnups and high temperatures in a fast neutron flux), is a major feasibility issue that is now being addressed in the fuels development and irradiation test program.

Fuels System Compatibility

Another major technical issue of concern to the SP-100 Program is to ascertain that the fuel, the refractory metal cladding surrounding the fuel, and the primary coolant (an alkali metal) are sufficiently compatible with one another to assure high temperature operating reliability during reactor lifetime. A major problem here is the potential for creep rupture of the cladding, allowing the fuel and coolant to come into contact. The consequences of such contact varies in severity depending on the magnitude of the rupture (a pin hole vs a large rupture of the cladding), the coolant composition (Li, Na, or NaK), the fuel composition (UO_2 or UN), and the temperature of the fuel-coolant interface. An isolated, nonpropagative incident of fuel-coolant interaction may be acceptable, but a propagation of loss of cladding integrity due to chemical or physical incompatibilities between the coolant, cladding, and fuel is clearly detrimental to the reactor system, particularly with respect to design lifetime.

Cladding degradation can occur by several distinct mechanisms. First, fuel constituents or fission products, or, alternatively, impurities in the coolant system, could chemically interact with the cladding material to change its composition, and, hence, alter its effectiveness as a barrier material. In addition, fuel or coolant components can migrate into the interstices of the cladding structure and accumulate at grain boundaries or voids, thus potentially altering, in a detrimental manner, the mechanical properties of the cladding material. Also, at the higher operating temperatures envisioned for the proposed SP-100 reactors, the possibility exists that products or components from the fuel or cooling system can migrate rapidly enough through the cladding material to cause unwanted changes to the reactor system even with a relatively intact cladding structure. Finally, the effects of prolonged irradiation on the properties of the cladding materials need to be considered. Irradiation induced changes to the structure of the cladding that would tend to reduce its creep strength or ductility could also be life threatening to the reactor system.

This whole series of potential fuel-cladding-coolant interactions is another area where there is a paucity of data or understanding for the materials involved under the severe operating conditions of the candidate SP-100 reactor systems. This also is a technical feasibility issue that is being focused on within the first phase of the SP-100 Program.

Obviously, not all of the technical issues identified above apply to all three of the reactor systems under consideration. In fact, although a large engineering development effort will be required, there are few feasibility questions about the fuel (beyond those which already exist for liquid-metal breeder reactors) for the low temperature reactor-Stirling engine option (1). The major technical challenge with this option is the development of the advanced Stirling conversion system itself.

In the case of the 1500 K liquid-metal-cooled reactor/thermoelectric option, fuel swelling as a function of burnup, temperature, fuel thermal gradient, and fuel stoichiometry is an area of technical uncertainty that needs to be addressed (1). Also of concern here are the issues of the chemical and physical compatibilities of the fuel-refractory metal cladding-alkali metal coolant system, and the effects of fast-flux radiation on the mechanical properties of the cladding material. These are areas where very few data exist, and which are being addressed by SP-100 scientists and engineers.

Finally, the fuel system in the high-temperature (in-core thermionics) reactor option also presents some major technical uncertainties of concern to the SP-100 Program (1,4). These involve fuel swelling rates and mechanisms, and subsequent swelling of the emitter system, and the physical and mechanical stability of the insulator materials over the reactor lifetime in the severe temperature and radiation environment inherent to this system.

THE SP-100 FUELS SYSTEMS DEVELOPMENT AND TESTING PROGRAM

To address the technical uncertainties defined in the previous section, a program of fuels and cladding development and irradiation testing has been started to provide the advances in materials technology necessary for the timely development of the proposed SP-100 reactor system (4). This program is composed of four distinct phases

1. Fuels and Materials Synthesis and Fabrication
2. Out-of-Reactor Materials Testing
3. Materials Compatibility Testing
4. In-Reactor Fuels and Materials Testing

Work on the first three phases of the program is currently underway, and planning is at an advanced stage to begin phase four. As now envisioned, phases one through three will continue until about mid 1985. Phase four will be started in late 1984 and continue through 1985. These initial activities, however, are scoping in nature and are timed to address some of the major feasibility questions by mid 1985 to support the final selection of a single concept for further engineering development. More detailed work, to provide necessary advances in fuels systems technology and to develop a fuels and materials irradiation data base, will be started at the beginning of the ground engineering phase of the SP-100 Program in late 1985.

Fuels and Materials Synthesis and Fabrication

Throughout this program, samples of the fuels and refractory alloys specified for the SP-100 reactor systems will be needed for data base development, fabrication development and properties testing, and for prototype reactor development. To avoid costly errors in judgment and programmatic delays, these must be materials with well characterized compositions, structures, and properties. With the exception of UO_2, none of the fuels systems component materials are readily available at the moment. The purpose of this first phase of the fuels program is to provide at the onset a supply of well characterized reactor fuels and refractory alloy cladding materials with known properties and compositions for both in- and out-of-reactor testing, and to develop the technology for reproducibly synthesizing these materials and fabricating them into component assemblies.

In this effort, UO_2 and UN fuel are being synthesized, characterized, and fabricated into prototypic forms. Fuels of varying stoichiometries, densities, porosities, and physical forms will be made (5). Although these activities for UO_2 appear to be reasonably straightforward, UN, of the desired characteristics for use in SP-100 work, has not been made for over 10 years, and, consequently, much developmental work must initially be done.

Likewise, a considerable effort is underway to assess the adequacy of the refractory alloy candidates for the proposed SP-100 reactors. These alloys systems (Mo, Ta, Nb, and W based alloys, for the most part) were chosen because of a perceived beneficial combination of physical, mechanical, and chemical properties. However, the data base on the behavior of these alloy systems under environmental conditions simulating those in a SP-100 reactor is extremely thin. In some instances, no data exist at all. To complicate matters, none of the alloys of interest are available on a regular commercial basis. Therefore, a second crucial component of the current SP-100 fuels development and testing effort is to prepare developmental quantities of the refractory alloys of interest, to thoroughly characterize their compositions and structures, and to develop and refine the technology to fabricate and join these alloys into the component geometries necessary for further testing.

Out-of-Reactor Materials Testing

The ultimate test for the fuels and cladding materials identified for the SP-100 reactors is to perform in-reactor simulated life testing with actual prototype component configurations. This is, of course, the most certain method of assessing the functional integrity of the various fuels and materials combinations of interest under the extreme environmental conditions that they will be subjected to in actual use. Such in-reactor testing, is, however, extremely expensive and time consuming. Therefore, work is being conducted on a number of out-of-reactor screening tests prior to embarking on an in-reactor test.

The focus of this work will be on accumulating necessary data on the physical and mechanical properties of the refractory alloys of interest to help narrow the many fuels and cladding combinations to those most feasible for each of the proposed reactor designs. An important consideration here is to assure that the materials chosen can withstand the mechanical loadings experienced during shuttle launch and orbital boost.

Among the physical properties of interest are alloy density, phase relationships, thermal conductivity, thermal expansion and emissivity, and the effects of thermal aging on alloy properties. The mechanical properties of most importance for the refractory alloys include the low temperature fracture toughness and ductile-brittle transition, and high temperature creep strength and fatigue. Both static and dynamic mechanical tests will be conducted, with the high temperature measurements carried out in vacuum to reduce the potential for alloy oxidation. Deformation and fracture mechanisms will be studied in detail where an understanding of such is deemed essential for effective materials use or selection. In addition to the parent materials, welded or joined specimens will also be included in the mechanical testing program. The effects of irradiation on the physical and mechanical properties of the most promising refractory alloy candidates will be examined in subsequent in-reactor tests.

Materials Compatibility Testing

As discussed earlier, assuring the compatibility of the various fuels systems components (fuel, cladding, and coolant) for long time periods under the adverse thermal, mechanical, and radiation environments of the SP-100 reactor is one of the most important feasibility issues facing reactor developers. These reactors represent an extremely dynamic operating environment under which the limits of materials integrity will be pushed, and where there is ample energy available to mobilize materials components and reaction products if a sufficient thermodynamic driving force exists. The long term consequences of the chemical interactions resulting in the fuels system environment must be well understood to assure program success.

The research here is directed at demonstrating the stability and compatibility of the fuel-cladding-coolant combinations of interest. Thermodynamic studies are being conducted to resolve the apparent conflicts in the published thermochemical data for hypostoichiometric UO_2. Resolution of this issue is necessary both to understand and to predict the high temperature compatibility of UO_2 with refractory alloy cladding materials. In related work, thermochemical studies are underway to determine the rates of oxygen or nitrogen diffusion from the UO_2 or UN fuel through the cladding material and into the heat transport fluid (Li). Also, the alkali metal corrosion resistance of the cladding alloys in the presence of UN or UO_2 is being investigated under a range of conditions. This information is necessary to understand the consequences of cladding breaches in the SP-100 fuel system.

The major product from these efforts will be a thermochemical model or models that will predict the chemical behavior of the fuels system components as a function of time, temperature, and composition which can be used to guide both the in-reactor tests and the further specification of materials in the reactor systems.

In-Reactor Fuels and Materials Testing

The centerpiece of the SP-100 fuels system development and testing activities over the next several years will be a comprehensive series of in-reactor tests designed to provide necessary data on fuel swelling and fission gas release, fuel-cladding mechanical interactions, fuel-cladding-coolant chemical compatibility, and irradiation effects on refractory alloy materials. An additional, longer term reason for conducting in-reactor tests is to develop a fuels systems performance data base with prototype fuel forms irradiated in a fast neutron environment.

The first in-reactor tests in the program are scheduled to begin in late 1984. These initial tests are of short duration and are designed to provide scoping information to support the down selection to a single SP-100 system concept in mid 1985. The goal of this in-pile testing is to provide preliminary data on the swelling behavior of UN and UO_2, and on the compatibility of irradiated fuel-cladding-coolant combinations at several temperatures and fuel burnups. In addition, these early reactor tests will provide an assessment of the effects of irradiation on the physical and mechanical properties of selected refractory metal alloys.

A technical plan is now being completed for the initial irradiation tests. These tests will be conducted in EBR-II under accelerated conditions utilizing a test capsule of proven design (Figure 1). As illustrated in the figure, the test capsules have provision for containing prototypic fuel pins surrounded by Li in a configuration simulating an SP-100 reactor environment. The final conditions and variables for these initial in-reactor tests are yet to be developed, but current thinking includes the parameters listed in Figure 2.

Assuming that the initial test matrix is inserted into the reactor in late 1984, the first low burnup capsules should be available for examination in early 1985. The remaining capsules, including some replacement inserts, will be retrieved from the reactor throughout the remainder of 1985.

Post-irradiation examination of the fuels and materials included in the in-reactor tests will include both nondestructive and destructive chemical and physical examinations designed to elucidate the important structures and properties of the irradiated samples.

SUMMARY

Three conceptually different compact fast reactor designs for 100-kWe space reactor systems are being assessed to determine the most feasible for further development into a fully flyable unit in the early 1990's. The major technical uncertainties associated with the fuels systems of these candidate reactors re fuel swelling and fission product behavior during irradiation and fuel-cladding-coolant compatibility. A fuels system development and testing program has been started to address these technical uncertainties, and to provide the necessary scientific support to the current technical assessment and advancement phase of the SP-100 Program.

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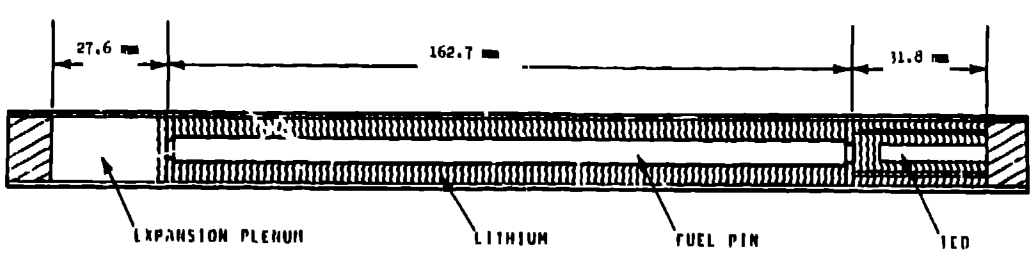

Figure 1. The Inner Section of the Test Capsule To Be Used For In-Reactor Assessment of SP-100 Fuels and Cladding Materials. Courtesy of HEDL

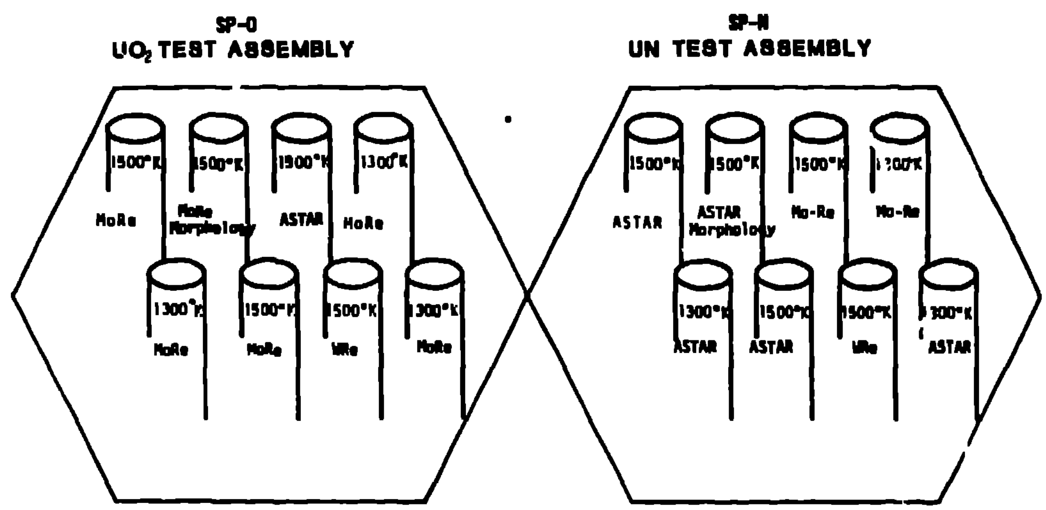

Figure 2. Preliminary SP-100 Fuels and Cladding Irradiation Test Matrix.
Courtesy of HEDL